Inductance, Capacitance, and Resistance of a Surrogate Exploding Wire

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Abstract-**Recent research into the exploding wire phenomenon has shown that capacitor grade metallized polypropylene film (MPPF) may perform as a surrogate to an exploding wire. The reaction of the MPPF to a high voltage capacitive discharge is similar to that of an exploding wire. A key difference that exists between the MPPF and the wire is that due to geometry, the stray capacitance and inductance of the film may have an effect on plasma formation. Tests have been performed on three types of MPPF to determine a relation, if any, between the impedance of the film and the formation of the plasma. MPPF samples of a fixed width with varying lengths were subjected to a 2.5 kV capacitive discharge. Trends in current, power, time duration, and energy as functions of length were compared to the measured inductance, capacitance, and resistance.**

I. INTRODUCTION

Research into the fusing properties of capacitor grade metallized polypropylene film (MPPF) has shown that certain geometries will respond to a high voltage capacitive discharge like an exploding wire. The initial strike, restrike, and dwell time apparent in the typical exploding wire current waveforms are all represented in a battery of experiments involving a number of different MPPFs. Previous research [1] showing a relationship between spatial distortions of the film and RLC impedance has prompted researchers to standardize a measurement method. Data from these measurements are then correlated to waveform data obtained by applying pulsed dc voltage to the film. Tests were performed on three types of MPPF categorized by the polypropylene substrate thickness and sheet resistance. These are high resistance 7 micron (7 Ω /sq), low resistance 7 micron (1 Ω /sq), and 5 mil (7 Ω /sq). The metallization consists of a thin (~100 Å) layer of aluminum, deposited onto the polypropylene substrate. The bulk MPFF was cut into 0.125" wide samples with lengths varying from 7.5" to 2".

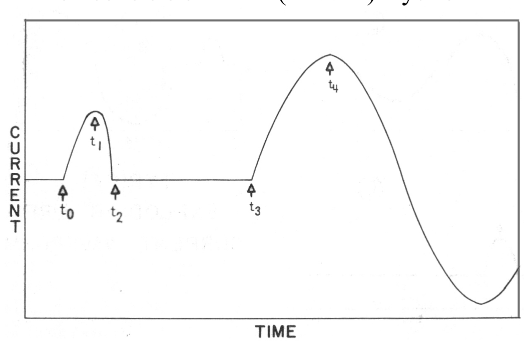

Fig. 1. Idealized Exploding Wire Waveform [2]

II. EXPLODING WIRES

The wave form of a typical exploding wire is shown in Fig. 1. After switch closure at time t_0, the wire undergoes ohmic heating until time t_1. At this point, the wire consists of a superheated liquid. The resistance of the wire begins to increase, with the corollary decrease in current, due to a phase change from liquid to gas. The period between t_2 and t_3, known as the dwell time, is a period of low conductivity when the wire is mainly a high density gas with dissolved metal vapors. At time t_3, the gas density is no longer maintained, and restrike occurs. This corresponds to a second current spike, controlled by the RLC time constants of the circuit. This restrike further lowers the density of the gas, until it can no longer conduct and the current settles to zero [2].

Fig. 2 shows a typical recorded current waveform from MPPF experiments performed at the Energy Systems Institute, with an inset showing detail on the first current peak. The time and current scales have the same units

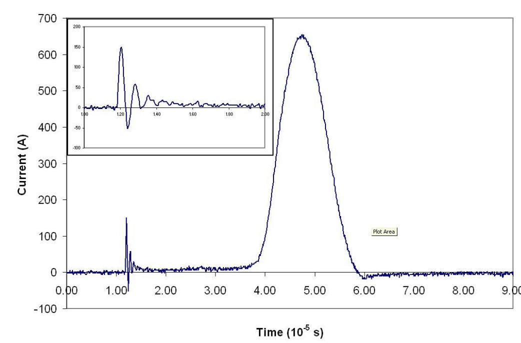

Fig. 2. Current (A) vs. Time (10^{-5}s) Low Resistance 7 micron, Inset: Initial Strike details

for both graphs. This specific graph is for low resistance 7 micron at 6" in length. Comparison of Fig. 1,2 shows a similarity in the current waveforms with an initial strike, restrike, and dwell time.

Previous research in this area was conducted by G.J. Woffinden [3,4]. This research resulted in a phenomenon similar to an exploding wire. A waveform with initial strike, restrike, and dwell time was observed. Tests were performed at similar energies with similar

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metallization thicknesses. A link between exploding wire parasitics and waveshape has been established by [1]. A link between MPPF parasitics and waveshape has been established by Buneo, et al. [1,5]

III. IMPEDANCE MEASUREMENT

Impedance measurements were performed using a GENRAD 1689 Precision RLC Digibridge. Flat clip leads connected the Digibridge to the MPPF sample. Due to prior difficulties in obtaining a consistent measurement [1], the film was laid flat with the metallization exposed for testing. This is the same positioning used for the pulsed dc testing. Lacking a permanent installation to measure the impedance of the MPPF film, the test apparatus needed to be reconfigured for each length of film. This involved adjustment of the test lead position and re-calibrating the Digibridge to prevent test setup impedances from being included in the measurements.

The Digibridge is capable of measuring series and parallel resistance, capacitance, and inductance, as well as dissipation factor and Q. The Digibridge was used to determine the resistance of the film, along with its series stray inductance and parallel stray capacitance. The Digibridge was unable to provide a measurement for parallel inductance or series capacitance. This fits with prior models for the film parasitics given by Zirnheld, et al. [5]

IV. PULSED DC TEST SETUP

Exploding wire and MPPF experiments are performed using a capacitive discharge circuit, shown in Fig. 3. The dc power supply provides a 0.5 to 3.5 kV charging voltage to a specially constructed low inductance 2600 nF capacitor bank. The closing switch is a MOS-Controlled Thyristor. The switch is electrically triggered via a function generator through an optically isolated gate driving network. Current data is fed to a Tektronix TDS7104 Digital Phosphor Oscilloscope via two Pearson Current Transformers. The current probes have scaling factors of 0.1V/A and 0.01V/A respectively, allowing researchers to capture both waveshape details and the overall waveform. Voltage is monitored through a Tektronix P6015 Voltage Probe with a 1000:1 scaling factor.

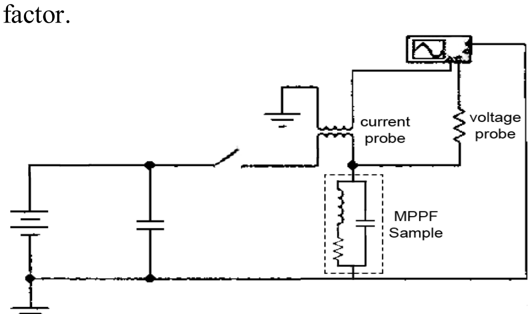

Fig. 3. Pulsed dc Test Setup

V. EXPERIMENTAL RESULTS

A number of different variables were tracked as functions of film length. These were initial strike current, restrike current, peak power, total energy, total time duration, initial strike rise-time (t_0-t_1), initial strike fall-time (t_1-t_2), dwell time (t_2-t_3), restrike rise-time (t_3-t_4), and restrike fall-time (t_4-current zero). The time durations noted correspond to time markers in Fig. 1. All experiments were performed at atmospheric pressure and room temperature with a charging voltage of 2.5 kV and a fixed film width of 0.125”. The current path and electric field were directed along the length of the film.

A. 5 mil MPPF

For the 5 mil film, it was noted that the measured inductance and resistance of the film decreased linearly with decreasing length. The capacitance decreased, with a spike at the minimum length of 2”. Initial strike and restrike currents increased with decreasing length, while peak power and time duration fluctuated up to a maximum at 2”. Dwell time and restrike rise-time fell with length, restrike fall time fluctuated to a maximum, and initial strike fall-time increased to a peak at 5”, then decreased. No trend was discernable in the initial strike rise-time.

B. Low Resistance 7 micron MPPF

The data for the low resistance 7 micron film followed that of the 5 mil rather closely. The deviations were in time duration and capacitance. Time duration decreased with a spike at 2”. Capacitance fluctuated to a maximum at 2”.

C. High Resistance 7 micron MPPF

In physical makeup, the high resistance 7 micron differs from the low resistance variety only in its resistance. The high resistance 7 micron differs from the 5 mil film only in the thickness of the polypropylene substrate. This aside, the reaction of the high resistance 7 micron is quite different. In subsequent trials, restrike occurred reliably for lengths of 5” or less. At 6”, restrike occurred only for an insignificant few samples, compared to the total number tested. At 7.5” and higher, restrike was not observed at all. Observation of the waveform showed an initial strike similar to that of the low resistance 7 micron or the 5 mil. During the dwell time, the current settled to zero.

The resistance and inductance of the film were high at 7.5” and 6” compared to the shorter lengths. Conversely, capacitance was low at 7.5” and 6” compared to the shorter lengths. Like the other two sample sets, initial strike and restrike (when it occurred) currents increased with decreasing length. Peak power and total energy fluctuated with maximums at 2”. Dwell times and restrike rise-times fell with length, while restrike fall-times (when they occurred) increased with decreasing length. No trends were observed in initial strike fall-times and total reaction times.

VI. DISCUSSION

A. High Resistance 7 micron

Discussion of the high resistance 7 micron in terms of its measured parasitics sheds some light on the issue of its behavior. If one were to compare only the quoted resistance values from the manufacturer, the results would be most puzzling. At shorter lengths, the film behaves nearly identically to the 5 mil and low resistance 7 micron. The initial strike current determined by the original equilibrium resistance is in line with those of the 5 mil film. Restrike appears in the current waveform uniformly in the shorter samples. This agrees with the extensive research by Woffinden [3], using various metallization metals, metallization thicknesses, substrate thicknesses, and applied voltages. That research, all using a fixed size, agrees with our short length data.

An interesting fact of the high resistance 7 micron experiments is that even with no restrike, an explosive event does occur. The reaction occurring in the film causes an audible compression wave. This leads us to believe that the factors preventing restrike are present during the dwell time (vapor phase). Also of note is the existence of the "chicken tracks" noted by Woffinden, et al. [4], in their investigations of films on glass substrates. These "chicken tracks" were determined to be a result of physical defects in the film. M. Taylor has noted that an exploding wire will, prior to the vapor phase, segment, and plasma will form around these segments [6]. Vlastós has noted a similar action of exploding wires [7]. It is possible that a similar mechanism exists here with the high resistance 7 micron film. Further research needs to be conducted to determine if the lack of restrike is due to fragmentation of the aluminum metallization, resulting in a premature break in the conduction path.

B. Low Resistance 7 micron and 5 mil

These film samples seem to fit with the accepted theory of an exploding wire. Including data from the high resistance 7 micron, it is noted that the low resistance (1 Ω/sq) sample has a much higher initial strike current (one order of magnitude). The high resistance samples (7 Ω/sq) have similar initial strike currents, and initial strike currents in general, increase with decreasing resistance. This leads us to believe that initial strike is related to the initial resistance of the metal.

Initial strike and restrike fall times and restrike rise-times are also resistance phenomena. At shorter lengths, the waveforms show greater and greater ringing in the fall of both restrike and initial strike. Long test leads, necessitated by the mobile test setup and safety considerations, may have introduced significant parasitic inductance into the test circuit. The shorter, lower resistance samples will damp the oscillations less than higher resistance samples. The restrike rise-time, theoretically controlled by the RLC resonances of the circuit, increases with decreasing length and inductance. The equation for an inductor (1), shows us that a lower inductance will allow a greater rate of change of current with fixed voltage. This allows a steeper current pulse.

$$v = L\frac{\mathrm{d}i}{\mathrm{d}t} \qquad (1)$$

The last data trend of note is the dwell time. Vlastós notes the dependence of dwell time on average electric field [6]. In this case, average electric field is defined as the applied voltage over the wire length. For both of his restrike mechanisms, dwell time decreases with increased applied voltage [8]. Extrapolating this to electric field, shortening the wire length has the same effect as increasing the applied voltage. Dwell times should decrease with increasing electric field, and they do.

VII. Conclusion

The effects of resistance, inductance, capacitance, and length on three varieties of metallized polypropylene film subjected to pulsed dc voltages have been discussed. The results show considerable similarity to the exploding wire phenomenon. Changes in all four variables produce waveform variations consistent with existing exploding wire models. Reproduction of prior exploding wire experiments with the MPPF needs to be conducted to completely match the two phenomena. The anomaly of the high resistance 7 micron film remains to be investigated. Future research should involve 5 mil films of different resistances. Results with the three films should also be validated with identical films from other manufacturers. The final conclusion to be drawn is based on prior research [1,5,9,10]. Prior research treated the reaction of the MPPF as surface flashover or fusing. Different film geometries here result in different phenomena. Both should be closely investigated to determine where the link is between the two. The lower energies required by this process allow finer tuning of the experiments. Applied voltage can be adjusted over a narrow range to determine which voltages cause which effects. This could provide a more accurate picture of the exploding wire phenomenon.

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REFERENCES

[1] J.D. Buneo, J.L. Zirnheld, K.M. Burke, J.P. Meade, J.C. Jones, W.J. Sarjent, "Capacitive and Inductive Influence on Fusing Behavior," Proc. 14th IEEE International Pulsed Power Conference, June 15-18, 2003, pp.1379-1381.

[2] W.G. Chace, "A Brief Survey of Exploding Wire Research," in *Exploding Wires*, vol. 1, W.G. Chace, H.K. Moore, Ed. New York: Plenum Press, 1959, pp.7-16.

[3] G.J. Woffinden, "Exploding Metal Films," in *Exploding Wires*, vol. 3, W.G. Chace, H.K. Moore,Ed. New York: Plenum Press, 964, pp.193-210.

[4] L. Zernow, F. Wright Jr., G. Woffinden, "High Speed Cinemicrographic Studies of Electrically Exploded Metal Films," in *Exploding Wires*, vol. 2, W.G. Chace, H.K Moore, Ed. New York: Plenum Press, 1962, pp.245-262.

[5] J.L Zirnheld, K.M. Burke, E.M. Halstead, A.D. Caulcrik, W.J. Sarjeant, "Geometric Modeling of Various Flashover Configurations in Metallized Polypropylene Film," *Pulsed Power Conference, 2005. Digest of Technical Paper. PPC-2005. 15th IEEE International,* 2005.

[6] A.E. Vlastos, "Restrike Mechanisms of Exploding Wire Discharges," *Journal of Applied Physics*, vol. 39, no.7, June 1968, pp.3081-3087.

[7] A.E. Vlastos, "Instabilities of Electrically Exploded Wires," *Journal of Applied Physics*, vol. 44, no. 4, April 1973, pp.1616-1621.

[8] A.E. Vlastos, "Dwell Times of Thin Exploding Wires," *Journal of Applied Physics*, vol. 44, no. 5, May 1973, pp.2193-2196.

[9] J.D. Buneo, J.K. Zirnheld, K.M Burke, W.J. Sarjeant, H. Moore, H. Singh, "Thin Film Geometry Influence on Fusing Wave Shape," *Power Modulator Symposium, 2004 and 2004 High-Voltage Workshop. Conference Record of the Twenty-Sixth International*, pp.571-574, 2004.

[10] J.D. Buneo, J.L Zirnheld, K.M. Burke, W.J. Sarjeant, M. Sussman, C. Freund, "Characterization of Pulse Induced Plasma Fueled by Aluminum Metallization," *Plasma Science, 2004. ICOPS 2004. IEEE Conference Record - Abstracts. The 31st IEEE International Conference on,* pg.451, 2004.